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A BROADBAND HIGH-GAIN BI-LAYER LOG-PERIODIC DIPOLE ARRAY (LPDA) FOR ULTRA HIGH FREQUENCY (UHF) CONFORMAL LOAD BEARING ANTENNA STRUCTURES (CLAS) APPLICATIONS

Nicholas A. Bishop and Mohammod Ali

University of South Carolina

Jason Miller, David L. Zeppettella, William Baron, and James Tuss

Structures Technology Branch
Aerospace Vehicles Division

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*//Signature//
DAVID L. ZEPPETTELLA
Work Unit Manager
Structures Technology Branch
Aerospace Vehicles Division

//Signature//
MICHAEL R. WIPPERMAN, Acting Chief
Structures Technology Branch
Aerospace Vehicles Division

//Signature//
FRANK C. WITZEMAN
Chief
Aerospace Vehicles Division
Aerospace Systems Directorate

*Disseminated copies will show "//Signature//" stamped or typed above the signature blocks.

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Nicholas A. Bishop and Mohammod Ali (University of South Carolina)
Jason Miller, David L. Zeppettella, William Baron, and James Tuss (AFRL/RQVS)

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University of South Carolina
Department of Electrical Engineering
Columbia, SC 29208

Structures Technology Branch (AFRL/RQVS)
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Air Force Research Laboratory, Aerospace Systems Directorate
Wright-Patterson Air Force Base, OH 45433-7541
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14. ABSTRACT

A broadband high-gain bi-layer log-periodic dipole array (LPDA) is introduced for conformal load bearing antenna structures (CLAS) applications. Under the proposed scheme the two layers of the LPDA are printed on two separate thin dielectric substrates which are substantially separated from each other. A meander line geometry is adapted to achieve size reduction for the array. The fabricated and tested array easily exceeds more than an octave of gain, pattern, and VSWR bandwidth.

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A Broadband High-Gain Bi-Layer LPDA for UHF Conformal Load Bearing Antenna Structures (CLAS) Applications

Nicholas A. Bishop, Jason Miller, David Zeppettella, William Baron, James Tuss and Mohammod Ali, *Senior Member, IEEE*

***Abstract*— A broadband high-gain bi-layer Log-Periodic-Dipole-Array (LPDA) is introduced for Conformal Load Bearing Antenna Structures (CLAS) applications. Under the proposed scheme the two layers of the LPDA are printed on two separate thin dielectric substrates which are substantially separated from each other. A meander line geometry is adapted to achieve size reduction for the array. The fabricated and tested array easily exceeds more than an octave of gain, pattern and VSWR bandwidth.**

***Index Terms* — Broadband antenna, array, log-periodic, LPDA, endfire, ultrawideband, UWB, CLAS.**

I. INTRODUCTION

The study of Log Periodic Dipole Antennas (LPDAs) dates back many decades [1]-[27]. LPDAs have been studied and designed for operation in free-space [1]-[4] as well as in printed configurations [5]-[8]. The works in [7, 8] propose a new technique to design and build stripline fed LPDAs in the microwave frequency band. These designs consider low dielectric constant materials and thin (few mm) printed embodiments. A printed meander dipole LPDA was proposed in [9] for operation from around 2-4.5 GHz. The peak array gain achieved was 7.5 dBi. Approximately 12% size reduced (Log Periodic Koch Dipole Arrays) LKPDAs were proposed in [10]. These microstrip LKPDAs operate from 2-3.2 GHz.

An LPDA design for ultrawideband pulse radiation has been proposed in [11]-[12]. More recently, a microstrip-fed band notched UWB LPDA was proposed in [13] for operation in the 4-10 GHz frequency range. The array peak gain was in the vicinity of 5 dBi.

It is apparent that many design examples of microstrip or stripline fed LPDAs exist for frequencies 1 GHz or higher. Similarly relatively low-gain (4 dBi) broadband UHF LPDAs also exist that consist of two very closely spaced (approximately 1 mm) dipole layers fed using a coaxial line [28].

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Nicholas Bishop and M. Ali are with the Department of Electrical Engineering, University of South Carolina, Columbia, SC 29208 USA (email. bishopna@email.sc.edu; alimo@cec.sc.edu). Jason Miller, David Zeppettella, William Baron, and James Tuss are with the AFRL, Wright Patterson Air Force Base, Ohio (email. Jason.miller.ctr@wpafb.af.mil, david.zeppettella@wpafb.af.mil, william.baron@wpafb.af.mil, james.tuss@wpafb.af.mil).

The focus of the present work is to introduce the design and development concepts of a broadband UHF LPDA that allows Conformal Load Bearing Antenna Structure (CLAS) integration. The CLAS concept [29-32] pioneered for air vehicle integration and application allows an antenna and its surrounding structure to become one seamless entity. This approach offers the optimum leveraging of materials and structures and significantly reduces the weight and drag associated with conventional antenna integration schemes. The integration efficiency of CLAS enables an air vehicle to host unconventionally large antenna leading to increased antenna performance potential.

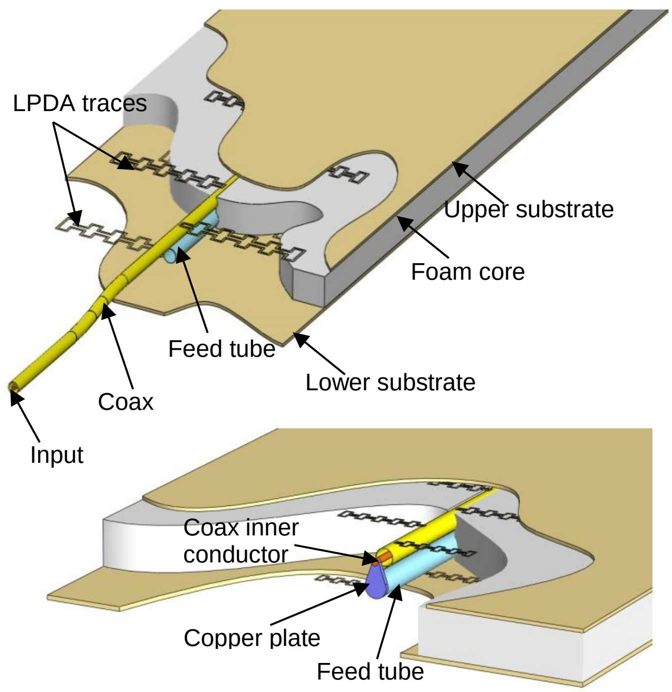

Fig. 1. Illustration showing the proposed CLAS LPDA in a structural sandwich. Top picture - longer dipoles or low band. Bottom picture – shorter dipoles or high band. Coax inner conductor shorted to feed tube using a copper plate.

The target RF performance requirements are: greater than an octave of gain, pattern, and VSWR bandwidths with a starting frequency of 350 MHz. Greater than 7 dBi of peak gain, large Forward to Backward ratio (F/B), and an endfire beam are desired. The proposed CLAS integration requirements are such that the antenna trace layers can be disposed of on two separate surfaces that are separated from each other by a substantial distance (1-2 inches). Further

CLAS integration requirement was to be able to fit the array within a space of 30 inches by 12 inches. In order to fit the width dimension a double meander type dipole geometry was used to achieve element length reduction of about 30%.

A schematic of the CLAS integration scheme is illustrated in Fig. 1 which shows that the LPDA meander traces are printed on two separate thin dielectric parallel surfaces. Given the traces are placed on the inside surface no additional radome is required. A low dielectric constant foam core is placed in between the antenna trace layers. The entire assembly is expected to be bonded together to create a unitized composite sandwich panel that is stiff and light weight. The sandwich composite panel has a greatly increased strength-to-weight ratio when compared to a similar RF performing LPDA fabricated on a single solid substrate. The stiffer antenna panel is suitable for applications on vehicle exteriors in direct contact with the free airstream without the need for a radome cover. The antenna will be integrated as a loadbearing panel that is part of the aircraft skin. Location and orientation of the panel on the aircraft will depend on the RF function of the antenna. Both fuselage and wing skins are viable locations.

The paper is organized as follows. First, the proposed array geometry is described followed by some initial simulation results. In order to obtain the design goal of the CLAS concept illustrated in Fig. 1 where the two dipole layers are substantially separated from each other various cases were investigated in a chronological manner. For ease of practical fabrication, the separation between the outside surfaces of the feed tube and the coax (Fig. 1) was maintained at 2.5 mm or greater. A preliminary study presented in Section III was performed to observe the dependence of the VSWR bandwidth on dielectric material loading. Second, a study presented in Section IV(A) was conducted to obtain a spaced bi-layer design consisting of various different dipole layer spacings. Third, a back to back design investigation was performed as presented in Section IV(B) followed by the analyses of a final back to back design presented in Section V that allows experimental fabrication on thin FR4 material. Next, the measured results of an experimental LPDA are presented followed by concluding remarks.

II. PROPOSED ARRAY GEOMETRY

The proposed UHF LPDA is illustrated in Fig. 2. The length and width of the total array are *AL* and *2L₁* respectively. One of the two dipole layers is shown in Fig. 2. Each layer is printed on a dielectric substrate with thickness, *t* and dielectric constant ε_{r1}. The two substrates containing the printed dipole elements are separated by a distance *H* which contains a dielectric medium with dielectric constant, ε_{r2}.

A. Element Selection

The geometry of the double meander element used as the building block of the LPDA is shown in Fig. 3. The length of each horizontal element is e_1 while the length of each vertical element is e_2. The trace width of the conductor that makes the double meander is defined as T_n. The resonant dimensions of a double meander dipole element were determined following the guidelines found in [33-35]. For example, a resonant straight conductor dipole operating at 350 MHz in free-space will be about 420 mm long if constructed using narrow width conducting strips. For the same frequency and same operating condition, a double meander dipole with e_1=10.5 and e_2=15 mm was found to be 300 mm long. Thus about 30% shortening in length was achieved with the help of 30 mm expansion in the lateral direction.

B. Array Design and Parameters

In Fig. 3, the elements shown using solid lines indicate the dipoles on the top layer while the elements shown using dotted lines indicate the dipoles on the bottom layer of the proposed structural antenna. The dipoles on the top layer are connected to the outer conductor of the feeding 50 Ω coaxial cable while the dipoles on the bottom layer are connected to a hollow conducting tube. The tube is in turn connected to the inner conductor of the feeding coaxial cable at the tapered edge of the array (see Fig. 4(c)). The dipole lengths, widths, conductor trace widths, and the inter-element spacings were all determined using the log-periodic equations below [36] and the well-known adjusted Carrel curves presented in [4]

$$\tau = \frac{L_n}{L_{n-1}} \qquad (1)$$

$$\sigma = \frac{D_{n-1}}{2L_{n-1}} \qquad (2)$$

The following design parameters, τ=0.917 and σ=0.169 were selected for a design gain of 9 dBi. The total number of elements of *N*=12 was chosen to ensure bandwidth allowance that can counteract the effects of dielectric loading.

Table I: Geometrical dimensions of the meander line LPDA in air.

Element #, n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Length, $\mathbf{2L_n}$ (mm)	300.0	275.1	252.3	231.3	212.1	194.5	178.4	163.6	150.0	137.5	126.1	115.7
Width, W_n (mm)	30.0	27.5	25.2	23.1	21.2	19.5	17.8	16.4	15.0	13.8	12.6	11.6
Trace Width, T_n (mm)	3.0	2.8	2.5	2.3	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.2
Distance, D_n (mm)	101.4	93.0	85.3	78.2	71.7	65.7	60.3	55.3	50.7	46.5	42.6	N/A
e_1 (mm)	10.5	9.6	8.8	8.1	7.4	6.8	6.2	5.7	5.2	4.8	4.4	4.0
e_2 (mm)	15.0	13.8	12.6	11.6	10.6	9.7	8.9	8.2	7.5	6.9	6.3	5.8

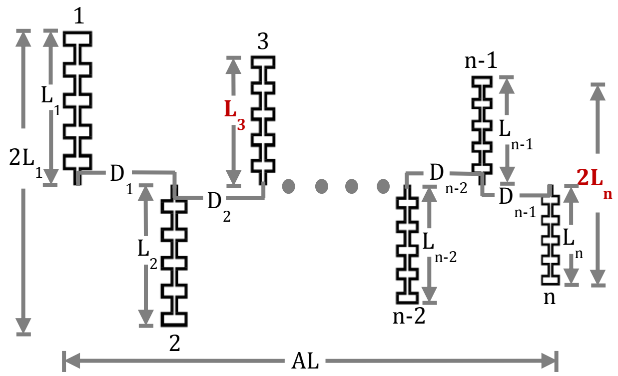

Fig. **2**. The proposed double meander line LPDA and its parameters. Only one layer is shown. The other layer is a copy and 180 degree reflection of the one shown here.

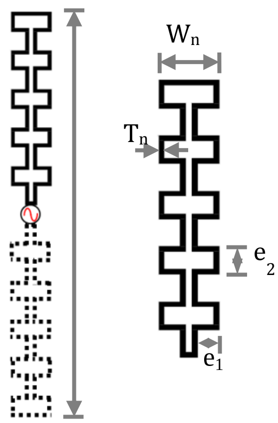

Fig. **3.** The double meander dipole element and its parameters.

III. INITIAL SIMULATION RESULTS **(BACK TO BACK DESIGN)**

A. LPDA in Free Space

As a starting point, a preliminary bi-layer LPDA was designed for operation from 350-700 MHz where all dipole elements were placed in free-space. The two layers were separated by a free-space distance of H = 10 mm, approximately half the desired separation for the proposed CLAS geometry shown in Fig. 1. The geometrical dimensions and other parameters of this LPDA are given in Table I. This array was modeled and simulated using HFSS. All conducting traces were modeled using copper as the conductor. The array feeding scheme in HFSS is illustrated in Fig. 4(a). The coax and the tube have the same outer diameter, *a*. The center conductor of the coax has a diameter, *b*. The dielectric constant of the material used in the coax is ε_r. At the onset of the cable a lumped gap source was used as the excitation. As can be seen in Fig. 4(b) the lumped gap source connects the center conductor of the coax to a conductive copper disk that is shorted to the outer conductor of the coax. At the other end of the coax the inner conductor is joined to the feed tube by a conducting U-shaped bridge to create the balanced line.

Simulated VSWR vs. frequency results for this LPDA are shown in Fig. 4(d) which clearly show that the array operates for more than an octave of bandwidth (350-750 MHz) within VSWR< 2. Patterns were computed at all frequencies but will not be shown here for brevity. Patterns in both the azimuth and elevation planes were found to be directional with peak realized gain from 7.8 to 9 dBi and F/B from 13.2 to 27.3 dB.

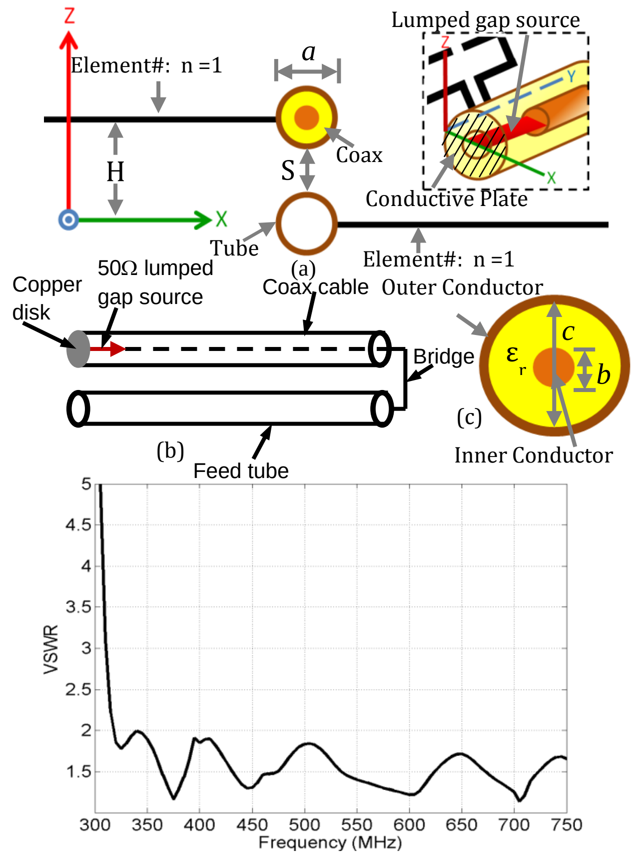

Fig. 4. (a) Feed coax and antenna trace location, HFSS feeding, (b) coax dimensions, and (c) simulated VSWR data of the UHF LPDA in air; H=10 mm, a=7.5 mm, S=2.5 mm, b=2 mm, c=6.7 mm, ε_r=2.2 mm, and **tanδ=0.001**.

B. Effects of Dielectric Material Loading

The effects of dielectric materials into the array were studied to understand the sensitivity of the array to dielectric materials. Two new cases were modeled and simulated. First, the loading effects of a 10 mm thick FR4 dielectric slab in between the two LPDA layers were analyzed. In the model, the areas where the coax and the tube were to be located the FR4 materials from there were removed. This was done by using the subtract operation in HFSS which created two vacuum holes inside the dielectric slabs to locate the feed coax and the tube. For Case 2, each of the two dipole layers was printed on its own FR4 substrate. Each layer (top and bottom) was 1.58 mm thick (Fig. 5). The space in between the two layers (H=10 mm) did not contain any dielectric material.

The results obtained from these two models and the baseline design in free-space are compared in Fig. 6. The solid line

represents the VSWR of the LPDA in free-space. The dashed line with the circles represents the results of the LPDA where each layer is printed on its own 1.58 mm thick FR4 substrate. Finally, the dashed line with the plus signs represents the results of the LPDA that contain a 10 mm thick FR4 dielectric slab in between the layers. The presence of a thick FR4 dielectric slab in between the layers causes significant detuning. The bandwidth also appears to have decreased. The VSWR, particularly at the high band, has deteriorated.

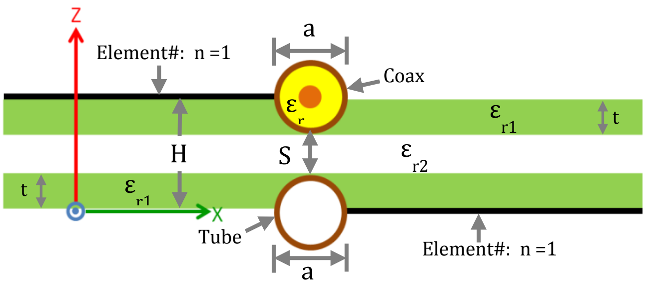

Fig. 5. The UHF LPDA supported by various dielectric materials.

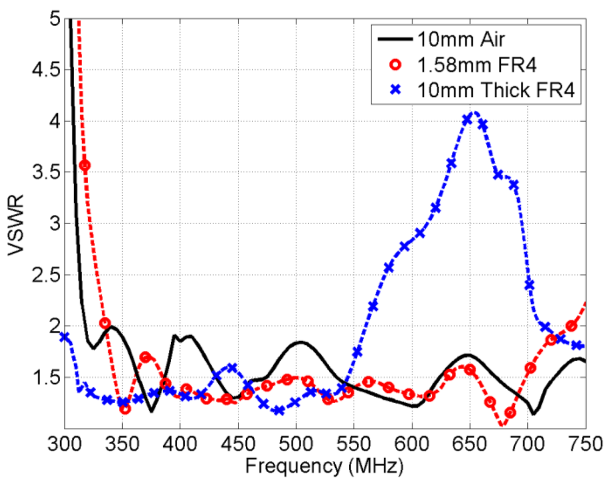

Fig. 6. Simulated VSWR comparison between the three LPDA cases: solid line - the baseline design in air ((thus both ε_{r1} and ε_{r2} is air, H=10 mm); dashed line with circles - layers on t=1.58 mm thick FR4 (thus ε_{r1} is FR4 but ε_{r2} is air, H=10 mm); dashed line with plus - Layers separated by a 10 mm thick FR4 dielectric slab (thus both ε_{r1} and ε_{r2} are FR4, H=10 mm). For all cases cable parameters are: a=7.5 mm, b=2 mm, S=2.5 mm, c=6.7 mm, ε_r=2.2, and tanδ=0.001.

By contrast, the array printed on 1.58 mm thick FR4 substrate (dielectric constant=4.4, loss tangent = 0.02) generally mimics that of the array in free-space. Interestingly, the VSWR for the latter is somewhat lower compared to the baseline design, likely due to the losses in the FR4 substrates. It is however clear that if each of the array layers are printed on 1.6 mm thick FR4 substrates they will provide more than an octave bandwidth under the current feeding scheme.

IV. SIMULATION RESULTS – SPACED BI-LAYER DESIGN IN FREE-SPACE

A. *Array Sensitivity on Separation Distance*

In Fig. 5, the array elements are separated by a distance 'H' while the feed lines are separated by a separation distance 'S.' Given the desired layer to layer separation distance, S of 25 mm or larger the sensitivity of the LPDA VSWR was simulated considering H=10, 15, 20, and 25.4 mm. Since the outer diameters of the coax and the feed tube were identical (7.5 mm), the resulting separation distance, S for these cases were 2.5, 7.5, 12.5, and 17.9, respectively.

It is well known that increasing S will result in an increase in the characteristic impedance of the balanced line [36]. This in turn will worsen the VSWR performance given the dipole and the coax cable impedances both being close to 50Ω. However, having a smaller diameter cable and feed tube is desirable from a structural integration point of view because it allows reduced mechanical load. To reconcile with these contradictory requirements the above cases were studied in order to observe and understand this sensitivity. The results of these simulations are shown in Fig. 7. It is clear that increasing S to 7.5 mm increases the VSWR to 2.5. Further increase in S increases the VSWR even further. Clearly as expected, a small S is needed to attain a good impedance match for the array.

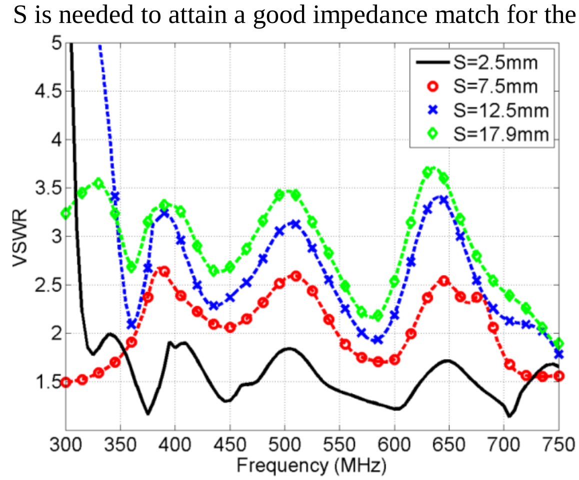

Fig. 7. The effect of the separation, *S* between the two layer LPDA. For all cases cable parameters are: a=7.5 mm, b=2 mm, c=6.7 mm, ε_r=2.2, and tanδ=0.001.

B. *Face to Face Design*

To obtain a large layer to layer separation, the feeding scheme shown in Fig. 8 was considered. If the coax and the tube are arranged as shown with respect to the antenna elements then the distance between the elements could be increased while keeping the distance between the coax and tube outer surfaces to a minimum. This arrangement also ensures that no additional dielectric cover or radome will be required because the antenna will be disposed of on the inside surface of the substrate. The space in between will be filled with a low dielectric constant foam which will accommodate the coax cable and the feed tube. Moreover, larger diameter (a) coax and feed tube was chosen to reduce the separation distance, S. Unlike the previous cases where both the coax and tube outer diameter was 7.5 mm for the case illustrated in Fig. 8 the diameter considered was 11 mm. This was a compromise design that allowed the use of a commercially available coaxial cable [37]. This arrangement with S=3.4 mm gave a layer to layer separation distance of 25.4 mm.

Simulated VSWR vs. frequency data for this new feeding arrangement with the new cable and feed tube are shown in

Fig. 9 (Case 2). For comparison, the VSWR data of the baseline design are also shown (Case 1). As seen, the VSWR data for the new arrangement (Case 2) show satisfactory performance which is in direct contrast with the data presented in Fig. 7 (S=17.9 mm case).

Computed peak realized gain data for Cases 1 and 2 are listed in Table II. It is clear that the gain values for Case 2 (larger separation) are similar to those for Case 1 except at the lowest frequency where the gain for the former is lower.

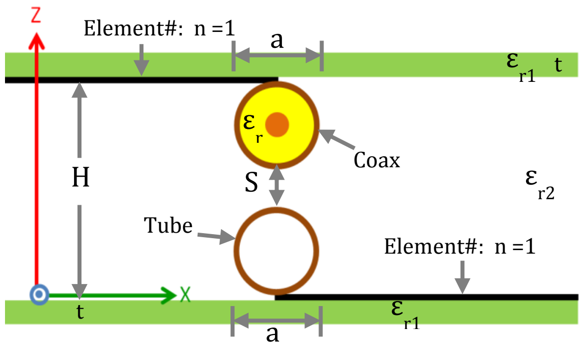

Fig. 8. New feeding arrangement for the UHF bi-layer LPDA, which allows increased separation between the two layers. **Face to Face design.**

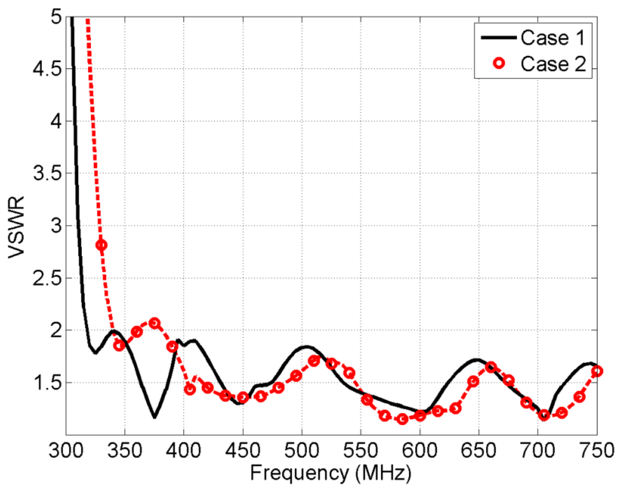

Fig. 9. Simulated VSWR results of the LPDA considering two cases: solid line representing the Baseline LPDA or Case 1 (cable parameters are: a=7.5 mm, b=2 mm, ε_r=2.2, c=6.7 mm; H = 10mm; S = 2.5mm) and the dashed line with circles represent the new LPDA feed arrangement or Case 2 (cable parameters are: a=11 mm, b=3 mm, ε_r=2.2, c=10.4 mm; H = 25.4mm; S = 3.4mm). In both cases ε_{r1}=1.0 and thus no dielectric substrate present.

Computed F/B data representing these two cases shown in Fig. 9 are listed in Table III. It is clear that the new feeding arrangement results in somewhat lower F/B throughout the frequency range. This is likely because of the increased separation between the two arms of the same dipole which are at 25.4 mm distance as opposed to 10 mm distance before.

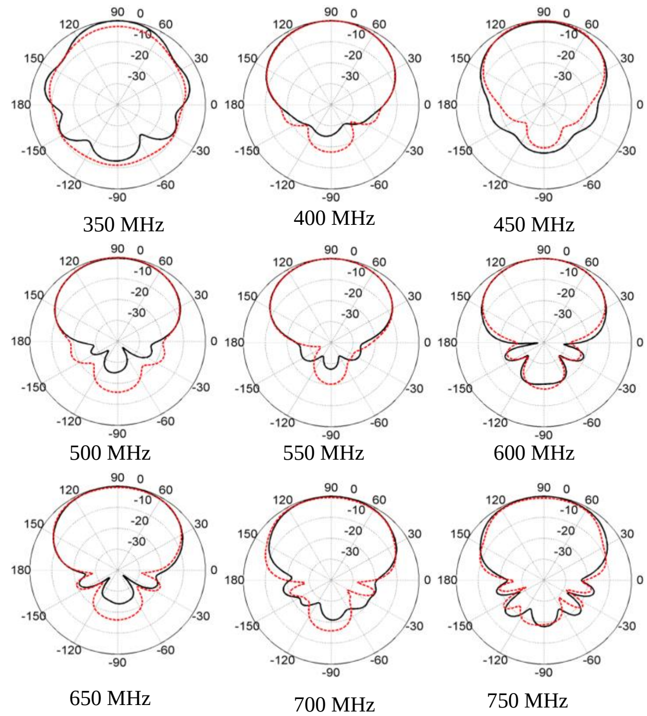

Fig. 10. Computed normalized patterns of the UHF LPDA in the elevation plane (yz-plane or phi = 90°). Two cases: solid line representing Case 1 (Cable parameters: a=7.5 mm, b=2 mm, ε_r=2.2, c=6.7 mm; H = 10mm; S = 2.5mm) and the dashed line representing Case 2 (Cable parameters: a=11 mm, b=3 mm, ε_r=2.2, c=10.4 mm; H = 25.4mm; S = 3.4mm). In both cases ε_{r1}=1.0 and thus no dielectric substrate present.

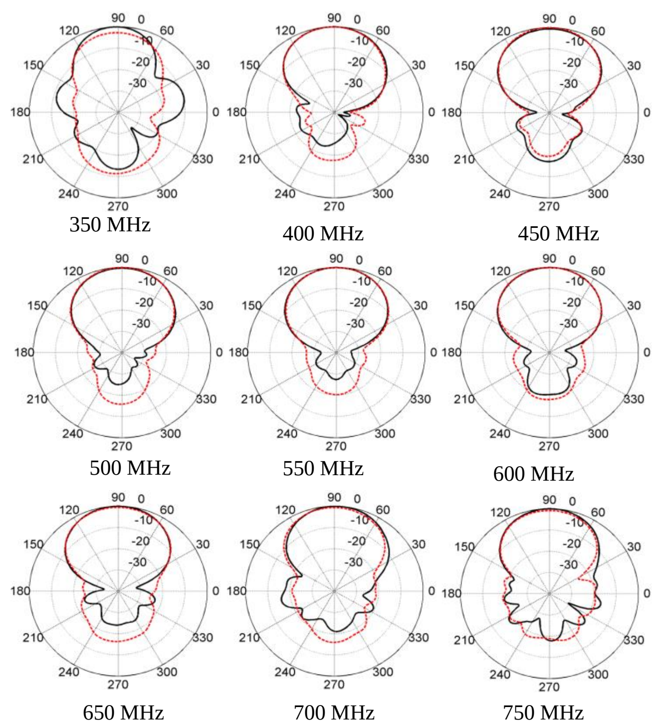

Fig. 11. Computed normalized patterns of the UHF LPDA in the azimuth plane (xy-plane or theta = 90°). Two cases: solid line representing Case 1 (Cable parameters: a=7.5 mm, b=2 mm, ε_r=2.2, c=6.7 mm; H = 10mm; S = 2.5mm) and the dashed line representing Case 2 (Cable parameters: a=11 mm, b=3 mm, ε_r=2.2, c=10.4 mm; H = 25.4mm; S = 3.4mm). In both cases ε_{r1}=1.0 and thus no dielectric substrate present.

Nevertheless, except for the lowest frequency the F/B is greater than 15 dB, which is satisfactory for most applications. Computed normalized radiation patterns in the elevation and azimuth planes for both cases are shown in Figs. 10 and 11. The patterns are directional, and symmetric. Within the frequency range of operation the half-power (3-dB) beamwidths in the elevation plane ranges from 64 to 92 degrees while that in the azimuth plane ranges from 38 to 64 degrees.

V. SIMULATION RESULTS – SPACED BI-LAYER DESIGN ON DIELECTRIC

Since the performance of the LPDA with the two layers being separated by a distance, H=25.4 mm was found to be satisfactory that design was considered for future fabrication and characterization. Further considerations were to explore the prospect of fabricating the array using a direct printing technique through a commercial manufacturer [38]. The commercial manufacturer spray prints antenna apertures and transmission lines using their proprietary techniques where they have specific dimensional limits and tolerances. Such as trace widths have to be within certain standard sizes or custom trace widths with small variations may become rather expensive. Based on those available trace width dimensions and the tolerances the UHF LPDA design was further adjusted to maintain performance in the 350-750 MHz frequency band. Those dimensions are only slightly different and are listed in Table IV. Also since the array will be fabricated on dielectric substrate materials the effect of dielectrics was also investigated. These results are shown in Fig. 12 which shows the VSWR data of the baseline design (original LPDA in free-space), adjusted final LPDA in free-space to fit commercial manufacturing trace width limits and tolerances, and the final adjusted LPDA printed on thin (1.58 mm thick) FR4 substrate layers. For the latter two cases H=25.4 mm and S=3.4 mm while for the baseline case H=10 mm and S=2.5 mm. It is clear that the final design with the adjusted dimensions and on FR4 operates satisfactorily within the 350-750 MHz bandwidth. The VSWR peaks are higher than the baseline design but are still satisfactory.

Computed peak realized gain (dBi) and the F/B (dB) of the final LPDA with adjusted dimensions and on thin FR4 substrates are listed in Table V. The gain varies between 6.2-9 dBi while the F/B varies between 5.3-19.1 dB.

Table II: Computed peak realized gain (dBi)of the UHF LPDA. In both cases ε_{r1}=1.0 and thus no dielectric substrate present.

Frequency (MHz)	350	400	450	500	550	600	650	700	750
Case 1: H = 10 mm, S=2.5 mm, Gain (dBi)	9.0	8.1	8.3	8.5	9.0	8.6	7.8	8.0	8.1
Case 2: H=25.4 mm, S=3.4 mm, Gain (dBi)	6.3	8.1	8.9	8.8	9.1	8.7	7.3	7.5	7.3

Table III: Computed Forward to Backward ratios (F/B) of the UHF LPDA. In both cases ε_{r1}=1.0 and thus no dielectric substrate present.

Frequency (MHz)	350	400	450	500	550	600	650	700	750
Case 1: H = 10 mm, S=2.5 mm, F/B (dB)	13.3	25.4	16.4	25.0	27.3	20.2	24.0	21.0	17.9
Case 2: H=25.4 mm, S=3.4 mm, F/B (dB)	8.0	17.5	19.4	15.8	20.3	17.9	15.8	15.3	18.0

Table IV: Original and new trace widths.

Element #, n	1	2	3	4	5	6	7	8	9	10	11	12
Original Trace Width, T_n (mm)	3.0	2.8	2.5	2.3	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.2
New Trace Width (mm)	2.54	2.54	2.54	2.286	2.286	1.778	1.778	1.524	1.524	1.27	1.27	1.143

Table V: Computed peak realized gain (dBi) and F/B (dB) of the final adjusted dimensions LPDA on thin FR4 layers.

Frequency (MHz)	350	400	450	500	550	600	650	700	750
Array realized gain (dBi) for final LPDA on FR4	6.2	7.8	9.0	8.4	8.7	8.6	7.0	7.8	7.1
Array F/B (dB) for final LPDA on FR4	5.3	12.2	18.3	19.1	19.1	17.7	15.2	11.2	15.6

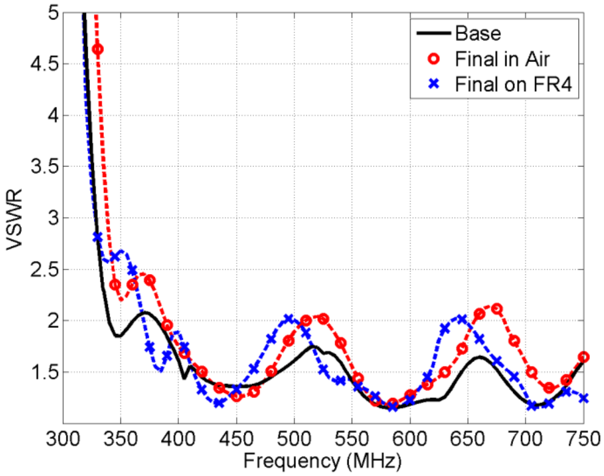

Fig. 12. Simulated VSWR results of the LPDA considering three cases: solid line representing the Baseline LPDA (cable parameters: a=7.5 mm, b=2 mm, ε_r=2.2, c=6.7 mm; H = 10mm; S = 2.5mm), the dashed line with circles represent the adjusted LPDA to meet commercial manufacturing trace width limits and tolerances, and finally the dashed line with the plus signs represents the adjusted LPDA on thin 1.58 mm FR4 layers. The latter two cases (a=11 mm, b=3 mm, ε_r=2.2, c=10.4 mm; H = 25.4mm; S = 3.4 mm).

VI. EXPERIMENTAL RESULTS

The proposed UHF LPDA was fabricated in-house at the University of South Carolina (USC) Microwave Engineering Laboratory (MEL) using photochemical etching. As because the complete array was about 3 ft long and 1 foot wide it was not possible to etch such a large aperture using our existing facilities. Instead, for each layer 12 inch by 12 inch 1.58 mm thick FR4 substrates were used to build the whole array. The two layers were separated from each other using plastic screws that were placed away from the conducting elements of the array. The array was fed using a 11 mm diameter coaxial cable (LMR 600 cable from Times Microwaves) [37] and a conducting copper tube. The outer insulation of the LMR 600 cable was removed in order to connect the antenna elements to the outer shield of the coax. Photographs of the fabricated array are shown in Fig. 13.

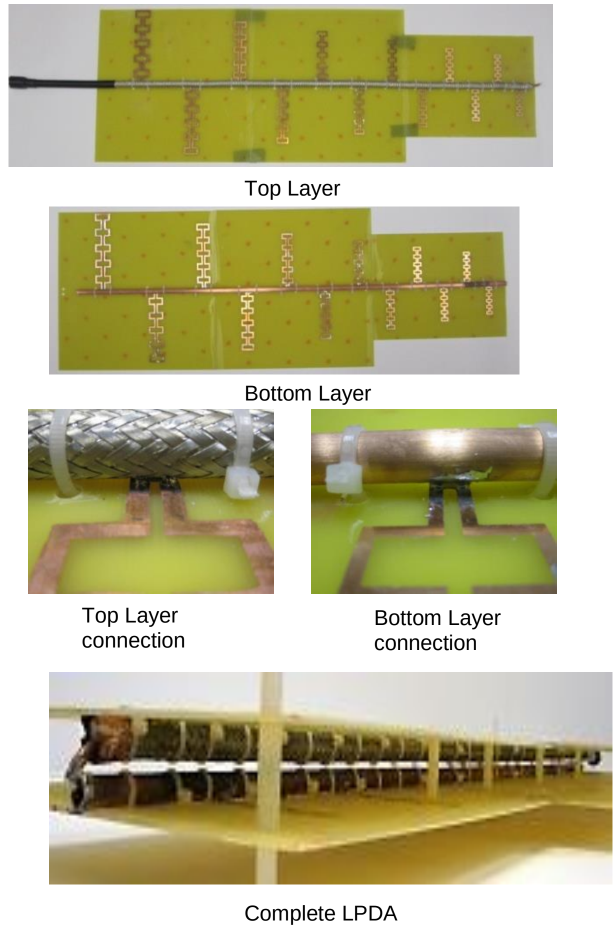

Fig. 13. Photographs of the fabricated LPDA.

Measured VSWR results of the fabricated LPDA are plotted in Fig. 14, which show that the array operates from 350-750 MHz. The VSWR shows a slightly higher peak between 450-500 MHz which is because of the difficulty in maintaining the S=3.4 mm distance between the outer surface of the coax and the tube that was maintained in the simulation models. It is expected that in practical manufacturing more precise distance control will be feasible either through better fixturing or through the use of constant thickness low dielectric constant insulating material.

Array radiation patterns and gain were measured in a Satimo chamber at the Wireless Research Center of North Carolina (WRCNC) [39]. Measured realized gain results are shown in Fig. 15. It is clear that for much of the frequency range the peak array gain is greater than 7 dBi. Only within a narrow frequency range the array gain is near 6 dBi. The array 7 dBi gain bandwidth easily exceeds an octave of bandwidth except for a narrow frequency range (660-670 MHz) where the gain is 6.5 dBi.

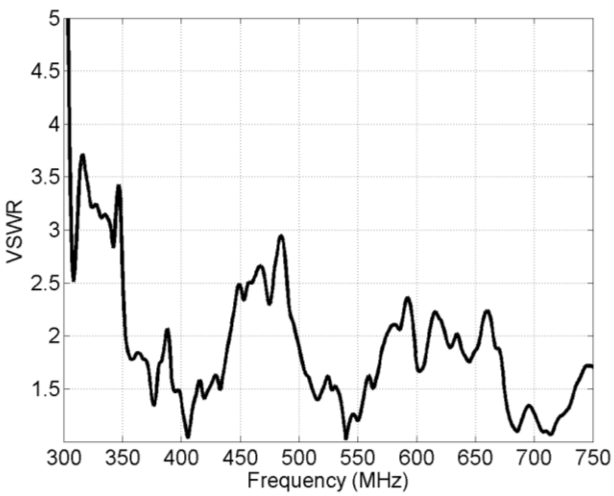

Fig. 14. Measured VSWR of the UHF LPDA shown in Fig. 13**.**

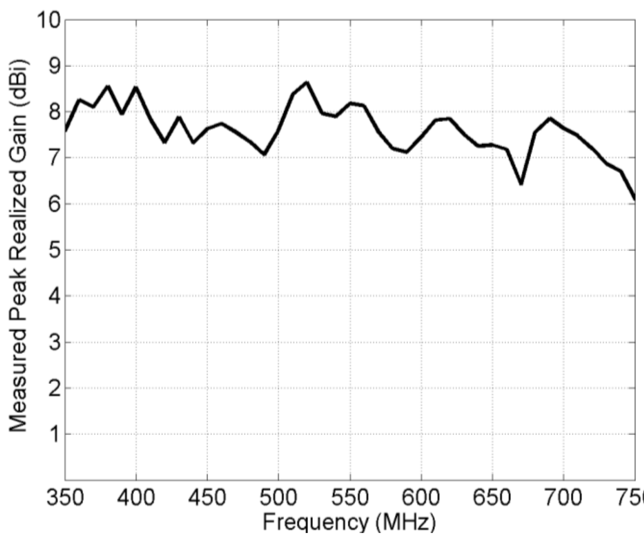

Fig. 15. Measured peak realized gain of the UHF LPDA shown in Fig. 13**.**

Measured normalized radiation patterns of the UHF LPDA shown in the photographs of Fig. 13 are shown in Figs. 16 and 17. The elevation plane patterns show directional beams with Half-Power Beamwidths (HPBW) in the range of 72 to 114 degrees while the azimuth plane patterns show HPBWs in the range of 54 to 72 degrees. The F/B ranges between 10-22 dB with an average F/B of 15 dB. Thus the experimental results clearly show a much higher F/B than the simulation results.

Table VI: Measured cross polarization at selected frequencies.

Frequency (MHz)	400	450	500	550	600	650	700	750
Cross-pol (dB) below	37.2	29.8	24.2	27.5	31.3	34.9	26.2	18

Measured cross-polarization data at selected frequencies are listed in Table VI. Cross polarization at 350 MHz is 17.9 dB (not listed in Table VI). Cross-polarization at most frequencies is suppressed below 20 dB except at the band edges where it is about 18 dB below the dominant polarization.

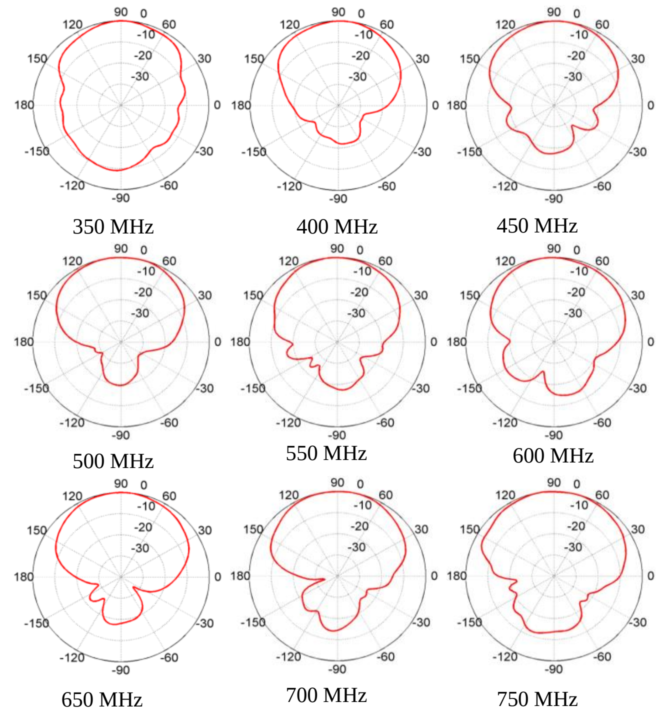

Fig. 16. Measured normalized Elevation Plane (phi = 90^{o}) patterns of the UHF LPDA shown in Fig. 12.

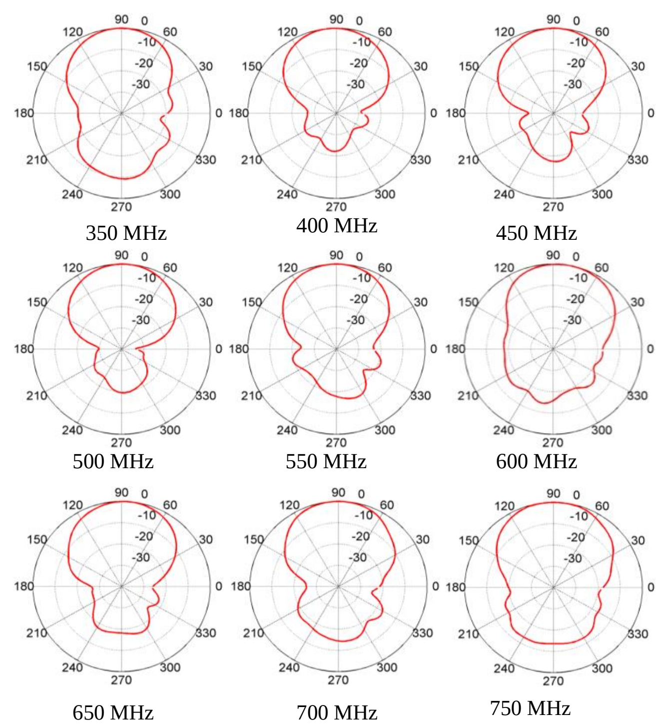

Fig. 17. Measured normalized azimuth plane (theta = 90^{o}) patterns of the UHF LPDA shown in Fig. 12.

VI. CONCLUSION

The study, design, fabrication and characterization of a broadband size-reduced UHF bi-layer CLAS LPDA are presented. The use of a double meander dipole as the building block allows a 30% reduction in the array width. Further

reduction is still possible as long as inter-element coupling does not deteriorate the array performance. It is clearly demonstrated that the two layers of the LPDA can be sufficiently separated from each other (1 inch to 1.5 inch) for the 350-750 MHz operation. The sensitivity of the array VSWR and radiation properties on dielectric materials, cable size, and cable orientation are studied. It is observed that a symmetric feeding arrangement consisting of same diameter cable and conducting tube with a small separation distance between them is preferred. The presence of thin FR4 dielectric materials has no significant detrimental effect on the array performance except for the gain reduction due to the high loss tangent of the FR4 material. Thus other low loss materials such as RO4003 will be a better choice. The fabricated array shows a VSWR bandwidth of 350-750 MHz. The gain of the fabricated array is above 7 dBi for most of the operating frequency band.

The design of the balanced feed line was a compromise to satisfy the need that the two antenna layers be substantially separated from each other. And thus the design depended on the availability of a feed coax with proper diameter for 25.4 mm total separation. Moreover, the practical difficulty of creating and maintaining a separation smaller than 3.4 mm in a lab environment directed us toward the design with a balanced line with higher characteristic impedance. Nevertheless, if one can maintain a spacing 'S' of say 1 mm between the two conductors of the feed line illustrated in Figs. 8 and 9 about 50Ω characteristic impedance can be obtained for the balanced line. This will increase the gain between 0.5 to 1 dB depending on the frequency.

The elevation and azimuth plane radiation patterns of the array show well defined directional beams with high gain and high F/B for most frequencies of operation. Further work will be needed in order to design and tune the array to suit a specific platform geometry and material system.

VII. REFERENCES

[1] R. Carrel, 'The design of log-periodic dipole antennas," *IRE International Convention Record.,* 1961, vol. 9, pp. 61-75.

[2] R. L. Carrel, "Analysis and design of the log-periodic dipole antenna," *University of Illinois Technical Report*, No. 52, Urbana, 1961.

[3] V. H. Rumsey, *Frequency Independent Antennas.* New York: Academic Press, 1966.

[4] W.L. Stutzman and G.A. Thiele, *Antenna Theory and Design*, John Wiley and Sons Inc., USA, 1998.

[5] P. B. Green and P. E. Mayes, *"50* Ω log-periodic monopole array with modulated-impedance microstrip feeder," *IEEE Trans. Antennas Propag.,* vol. AP-22, pp. 332-334, March 1974.

[6] K. M. Keen, "A planar log-periodic antenna," *IEEE Trans. Antennas Propag.,* vol. AP-22, pp. 489-490, May 1974.

[7] C.K. Campbell, I. Traboulay, M.S. Suthers, and H. Kneve, "Design of a Stripline Log Periodic Dipole Antenna,'' *IEEE Trans. Antennas Propag.,* Vol. AP-25, pp. 718-721, Sept. 1977.

[8] R. R. Pantoja, A. R. Sapienza, and F. C. Medeirosfilho, "A Microwave Printed Planar Log-Periodic Dipole Array Antenna,'' *IEEE Trans. Antennas Propag.,* Vol. AP-35, pp. pp. 1176-1178, Oct. 1987.

[9] A. A. Gheethan and D. E. Anagnostou, "The Design and Optimization of Planar LPDAs,'' *PIERS Proceedings*, Cambridge, USA, July 2008, pp. 478-481.

[10] D. Anagnostou, J. Papapolymerou, M.M. Tentzeris, and C.G. Christodoulou, "A Printed Log-Periodic Koch-Dipole Array (LPKDA),'' *IEEE Antennas and Wireless Propagat. Lett.,* Vol. 7, 2008, pp. 456-460.

[11] F. Merli, J.-F. Zürcher, A. Freni, and A.K. Skrivervik, "Analysis, design and realization of a novel directive ultrawideband antenna,'' *IEEE Trans. Antennas Propag.,* Vol. 57, pp. 3458-3466, Nov. 2009.

[12] A. Calmon, G. Pacheco, M.A.B. Terada, "A novel reconfigurable UWB log-periodic antenna,'' *IEEE Antennas and Propagation Society Interntaional Symp. Dig.,* 2006, pp. 213-216.

[13] A. Khaleghi, H.S. Farahani, and I. Balasingham, *"*Impulse Radiating Log-Periodic Dipole Array Antenna Using Time-Reversal Technique,'' *IEEE Antennas and Wireless Propagat. Lett.,* Vol. 10, 2011, pp. 967-970.

[14] C. Yu, W. Hong, L. Chiu, G. Zhai, C. Yu, W. Qin, and Z. Kuai, "Ultrawideband Printed Log-Periodic Dipole Antenna With Multiple Notched Bands,'' *IEEE Trans. Antennas Propag.,* Vol. 59, pp. 725-732, Mar. 2011.

[15] G.A. Casula, P. Maxia, and G. Mazzarella, "A printed LPDA with UWB capability,'' *2010 International Workshop on Antenna Technology (IWAT),* pp. 1.4.

[16] L. Shan, L. Xiaofeng, Q. Jinghui, "A novel miniaturized ultra wideband log-periodic antenna,'' *2010 International Conference on Ultrawideband and Ultrashort Impulse Signals (UWBUSIS),* pp. 246-248.

[17] B. Turetken, "Design and realization of printed LPDA in UHF band,'' *10th International Conference on Mathematical Methods in Electromagnetic Theory*, 2004., Sept. 14-17, 2004, pp. 295 – 297.

[18] M. N. A. Karim, M. K. A. Rahim, H. A. Majid, O. Ayop, M. Abu and F. Zubir, "Log periodic fractal Koch Antenna for UHF band applications,'' *Progress In Electromagnetics Research*, PIER 100, 201-218, 2010.

[19] P. Li, X. Jiang, X. Liu, H. Shi, X. Lu, "Research on the relation between Printed Log-Periodic Antenna's feed and bandwidth,'' *2010 International Symposium on Signals Systems and Electronics,* pp. 1-3.

[20] A. Moallemizadeh, H.R. Hassani, and S.M.A. Nezhad, "Wide bandwidth and small size LPDA antenna,'' *2012 6th European Conference on Antennas and Propagation (EUCAP),* pp. 1-3.

[21] B. Gong, L.H. Su, Y.-Z. Yin, H. Ma, Q.-R. Zheng, "A novel log-periodic dipole antenna with distributed inductive load,'' *2012 2nd International Conference on Consumer Electronics, Communications and Networks (CECNet),* pp. 61 – 63.

[22] X.L. Zhang and H.-T. Gao, "An optimum design of miniaturized high frequency inverted-V log-periodic dipole antenna,'' *2011 IEEE CIE International Conference on Radar (Radar),* pp. 1185 – 1188.

[23] Q. Zhao and Z. Yin, "The influence of feed tube changes on performance of log periodic dipole antenna,'' *2012 International Conference on Microwave and Millimeter Wave Technology (ICMMT),* pp. 1 – 4.

[24] H. Zhou, N.A. Sutton, and D.S. Filipovic, "W-band endfire log periodic dipole array,'' *2011 IEEE International Symposium on Antennas and Propagation (APSURSI),* pp. 1233 – 1236.

[25] J.-M. Lee, H.-J. Ham, H.-K. Ryu , J.-M. Woo, B.-J. Park, K.-S. Lee, "Miniaturization of log-periodic dipole array antenna using triangular meander structure,'' *2012 IEEE International Conference on Wireless Information Technology and Systems (ICWITS),* pp. 1 – 4.

[26] D.N. West and S.K. Sharma, "Frequency reconfigurable compact multiband quasi-log periodic dipole array (QLPDA) antenna for wireless communications,'' *2010 IEEE Antennas and Propagation Society International Symposium (APSURSI),* pp. 1 – 4.

[27] M. Hilbert, M.A. Tilston, and K.G. Balmain, "Resonance phenomena of log-periodic antennas: characteristic-mode analysis,'' *IEEE Trans. Antennas Propag.,* Vol. 37. pp. 1224-1234, 1989.

[28] Hyperlog 7040 [online available: http://www.aaronia.com/?id=6

[29] M.A. Hopkins, J.M. Tuss, A.J. Lockyer, J.N. Kudva, "Smart Skin Conformal Load-Bearing Antenna and Other Smart Structure Developments,'' *Nato Workshop on Smart Electromagnetic Structures*, 25-26 Nov. 1996.

[30] A.J. Lockyer, K.H. Alt, R.W. Kinslow, H.-P. Kan, J.N. Kudva, J.M. Tuss, and A.C. Goetz, "Development of a structurally integrated conformal load-bearing multifunction antenna: overview

of the Air Force Smart Skin Structures Technology Demonstration Program,'' *Proc. SPIE* 2722, Smart Structures and Materials 1996: Smart Electronics and MEMS, 55 (May 20, 1996).

[31] A.J. Lockyer, K.H. Alt, J.N. Kudva, R.W. Kinslow, A.Goetz, “Conformal load-bearing antenna structures (CLAS): Initiative for multiple military and commercial applications,'' SPIE Vol. 3046, pp.182-196, 1997.

[32] C. You, M.M. Tentzeris, and W. Hwang, “Multilayer Effects on Microstrip Antennas for Their Integration With Mechanical Structure,'' *IEEE Trans. Antennas Propagat.,* vol. 55, Apr. 2007, pp. 1051-1058.

[33] M. Ali, *Analyses of Self-Resonant Bent Antennas*, Ph.D. Dissertation, University of Victoria, BC, Canada, 1997.

[34] M. Ali, S.S. Stuchly, and K. Caputa, “A Wide-Band Dual Meander-Sleeve Antenna, ”*Journal of Electromagnetic Waves and Applications*, Vol. 10, No. 9, 1996, pp. 1223-1236.

[35] M. Ali, G.J. Hayes, H.-S. Hwang and R.A. Sadler, “Design of a Multi--Band Internal Antenna for Third Generation Mobile Phone Handsets,” *'' IEEE Trans. Antennas Propag.*, vol. 51, no. 7, July 2003, pp. 1452-1461.

[36] C.A. Balanis, Antenna Theory Analysis and Design, John Wiley and Sons, USA, Third Edition.

[37] Times Microwaves Inc. USA. online available: [http://www.timesmicrowave.com/].

[38] Mesoscribe Technologies Inc. USA. online available: [http://www.mesoscribe.com/services/direct-write-fabrication/].

[39] Wireless Research Center of North Carolina (WRCNC); online available: [http://www.wirelesscenter-nc.org/].